PERFORMANCE OF A DOUBLE-JUNCTION SOLAR CELL UNDER VARIOUS ENVIRONMENTAL CONDITIONS

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Abstract

PV manufacturers only provide performance of a PV technology at a standard test condition (STC) where the irradiance at 1000 W/m^2, spectrum of AM1.5 and a module temperature at 25°C. This information is inadequate to represent the performance of the PV device under real operating conditions. This paper investigates the performance of a double-junction solar cell under different climatic conditions, i.e. temperature, irradiance, solar spectrum, and the angle of incidence. The effects of environmental conditions on the cell's performance are observed by simulating their current and voltage characteristics using a one-diode. The results show that the short-circuit current of a double-junction device is spectrally sensitive to the incident irradiance and solar spectrum. When the angle of incidence is greater than 60°, the maximum power of a double-junction solar cell reduces significantly.

Keywords: double-junction solar cell; environmental effects; one diode model

Introduction

A double-junction solar cell is made by combining two single-junction solar cells monolithically in series. The performance of this solar cell under different environmental conditions is determined by the current and voltage (I-V) characteristics of its individual single-junction solar cells. Due to the series connection, the total current flowing in a double-junction solar cell is equal. This condition rarely occurs in a realistic operating condition.

The current generated by individual sub-cells depends on the several factors, i.e. the light intensity incident on the cell, the cell's temperature, the solar spectrum and the angle of incidence. As the individual sub-cells are designed with different band gap energy, their spectral response curves are different. The cell on the top usually has higher band gap energy than the bottom cell. As a result, the top cell absorbs higher photon energy and becomes a spectral filter for the spectral irradiance that is received by the bottom cell. The lower current produced by one cell can limit the current that is produced by another cell and becomes a current limiting cell for the entire cell at certain spectral conditions. This cell's behavior is uneasily detected because the information of device performance that is provided by the PV manufacture is only limited to the standard test condition (STC) and the nominal operating condition (NOCT). If the performance at STC is used for predicting an annual energy yield of a PV device, the result will be inaccurate. It is because STC only shows the device performance at one operating condition while the weather conditions change over time. As a result, the individual I-V characteristic curves of a double-junction solar cell are also varied with the weather conditions.

Understanding the performance of a double-junction solar cell under different environmental conditions is imperative for predicting its energy yield, optimizing the cell design and accurate sizing of a PV system. Due to some limitations in the ability of a solar simulator to provide a large range of environmental conditions for I-V measurements, a simulation approach is required. Therefore, this paper aims to contribute to better understanding of how different environmental factors influencing the performance of a double-junction solar cell and to quantify the magnitude of their influences on different performance parameters.

Simulation of a double-junction solar cell

The structure of a simulated double-junction solar cell is shown in Fig. 1. It consists of two single-junction solar cells indicated as the top and the bottom cells. As shown in Fig.1, the top cell filters the solar spectrum absorbed by the bottom cell.

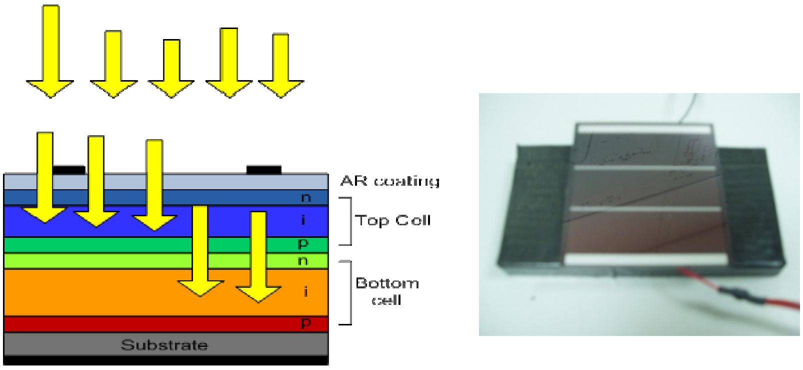

Figure 1. Structure of a double-junction solar cell and the absorption of photon energy in its individual sub-cells.

The equivalent circuit diagram of the simulated double-junction solar cell is shown in Fig.2. In this figure, each sub-cell is represented by five device parameters which are the photocurrent Iph, the diode saturation current I_D, the shunt Rp and series resistances Rs, and the diode ideality factor n.

A simple one-diode model is used to simulate the current and voltage characteristic curve of a double-junction solar cell at STC. The five device parameters that are used for simulating the top and bottom cells are shown in table 1.

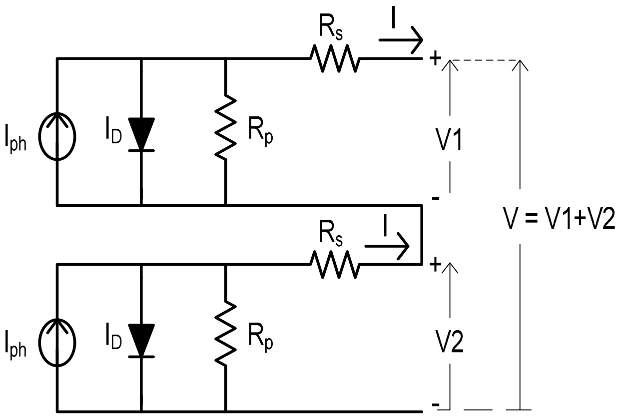

Figure 2. Equivalent electrical diagram of a double-junction solar cell.

Table.1. Device parameters used in the simulation of the top and bottom cells of a double-junction solar cell.

Parameters	Top cell	Bottom cell
I_{ph} [Amp]	0.040	0.034
I_o [Amp]	1.20×10^{-9}	1.50×10^{-9}
R_s [Ω]	0.001	0.002
R_p [Ω]	10000	12000
n	1.1	1.2

The short-circuit current generated by the top cell is modeled by assuming that most of the photons at the short wavelength intervals of solar spectrum are absorbed by the top cell. It is expressed in Eq. (1) as follows:

$$I_{ph,top} = A \cdot (q/hc) \int_{\lambda 1}^{\lambda 2} \lambda E(\lambda) QE_{top}(\lambda) d\lambda \qquad (1)$$

Where A is the cell's area, h is Planck's constant, 6.6262×10^{-34}Js, c is the speed of light, 2.997925×10^{8}m/s, λ is the wavelength in nm, $E(\lambda)$ is the spectral irradiance at the plane of array (Watt/m^2/nm), $QE_{top}(\lambda)$ is the external quantum efficiency of the top cell calculated as $(hc/q\lambda)*SR(\lambda)$.

Similarly, the short-circuit current generated by the bottom cell is calculated by assuming that the cell only receives the remaining spectrum after being filtered by the top cell. It is written in Eq.2 [1].

$$I_{ph,bottom} = A \cdot (q/hc) \int_{\lambda_1}^{\lambda_2} \lambda E(\lambda) \left[1 - QE_{top}(\lambda)\right] QE_{bottom}(\lambda) d\lambda \qquad (2)$$

Where the QE_{bottom} is the external quantum efficiency of the bottom cell.

Once the short-circuit current of the top and the bottom cells have been determined, the following step is to determine the matched current between the top and the bottom cells using the bisection approach. The matching current is calculated as a function of device voltage which is the summation of the voltage of its sub-cells as shown in Eq.3. [2].

$$I = I_{ph} - I_o \left[\exp\left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right] - \frac{V + IR_s}{R_p} \qquad (3)$$

Where I_{ph} is the photocurrent in Ampere, I_o is the diode saturation current in Ampere, q is the electric charge, $1.6\text{x}10^{-19}$ Coulomb, V is the total voltage of the top and the bottom cells, T is device temperature in Kelvin and k is the Boltzmann constant, $1.38\text{x}10^{-23}$J/K.

The spectral response (SR) curves which are the ratios of the short-circuit current and the power incident on the cell at specific wavelengths of the top and the bottom cells are obtained from the SR measurement as shown in Fig.3. These SR curves are used in the calculation of the cell's short-circuit current.

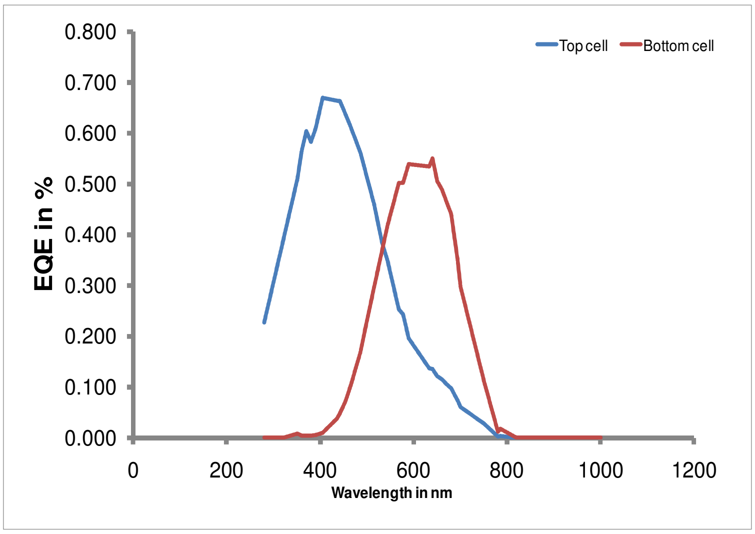

Figure 3. Spectral response of the top and bottom cells of the simulated double-junction solar cell.

The entire simulation process of a double-junction solar cell is shown in Fig.4.

To investigate the effects of different irradiances on a double-junction cell, the irradiance falling onto the device was varied by 10% to 90% from the intensity at the STC as shown in Fig.5 and the same spectrum AM1.5 is applied.

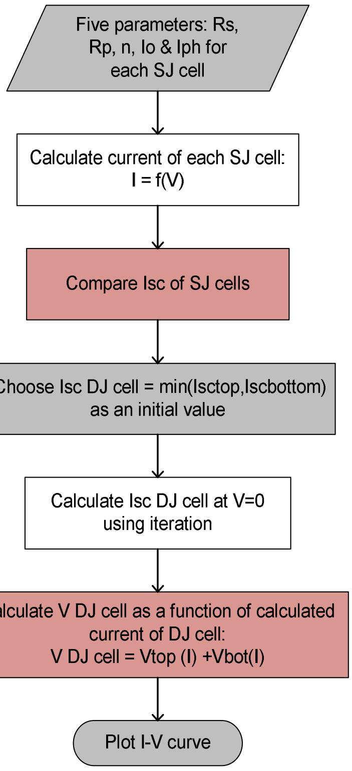

Figure 4. Flowchart for simulating a current and voltage (I-V) characteristic curve of a double-junction solar cell.

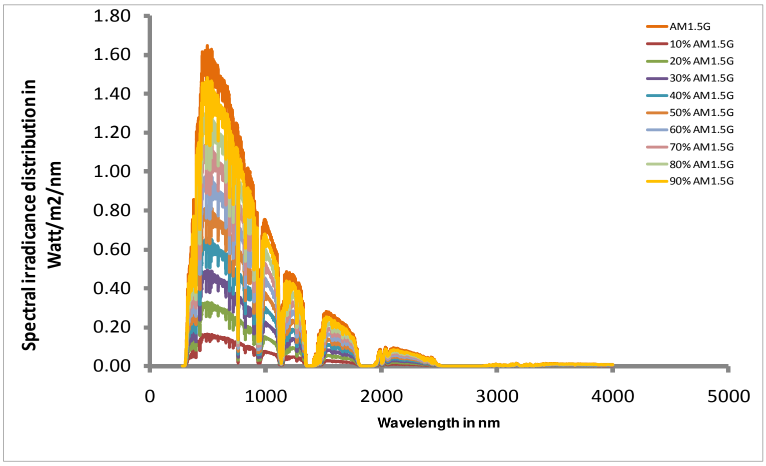

Figure 5. Variations of irradiance levels used in the simulation.

The spectral effects are observed by varying the incident spectrum from AM1 to AM 6 as shown in Fig.6. These spectra are obtained using the SMART software. It is calculated under the clear sky condition with the angle of incidence at 45°. As shown in Fig.6, the solar spectrum shifts toward the red ends (low energy photons) at higher air mass. Changes in the cell's temperature are made from 0°C to 85°C and the variations in the angle of incidence of the direct irradiance are varied at 0°, 60° and 120°.

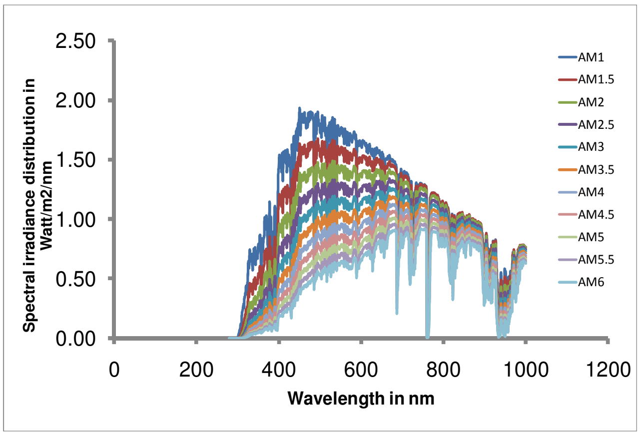

Figure 6. Variations in the incoming solar spectrum to the surface of a double-junction solar cell.

Results and Discussions

The effects of the environmental factors on the performance parameters, i.e. the power at the maximum point, the open-circuit voltage, the short-circuit current and the fill factor of a double-junction solar cell are as follows:

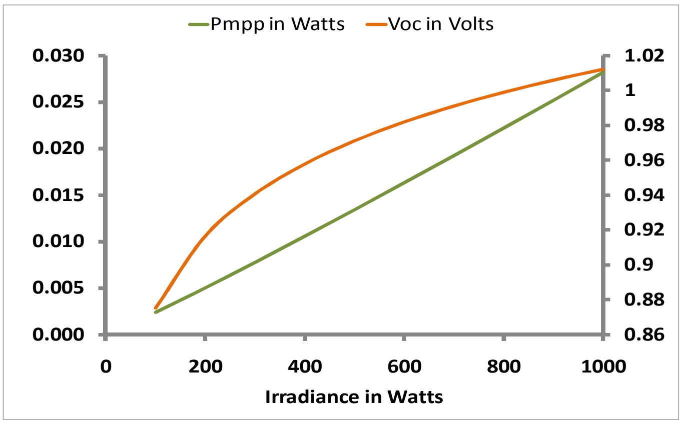

Figure 7. Effects of different irradiances on the power at the maximum point and the open-circuit voltage.

Effects of Irradiances

Changes in the device's performance due to variations in the total irradiance received the cell can be seen in Fig. 7 and 8. It is shown that the increase in the short-circuit current and the maximum power is proportional to the increase in the irradiance level at a fixed temperature condition (25°C). At low irradiance level, the simulated double-junction solar cell produces a low open-circuit voltage at 0.88 Volt. The open-circuit voltage and fill factor change logarithmically with the increase in the irradiance level. Both of them increase rapidly at low irradiance level and gradually increase at high irradiance level.

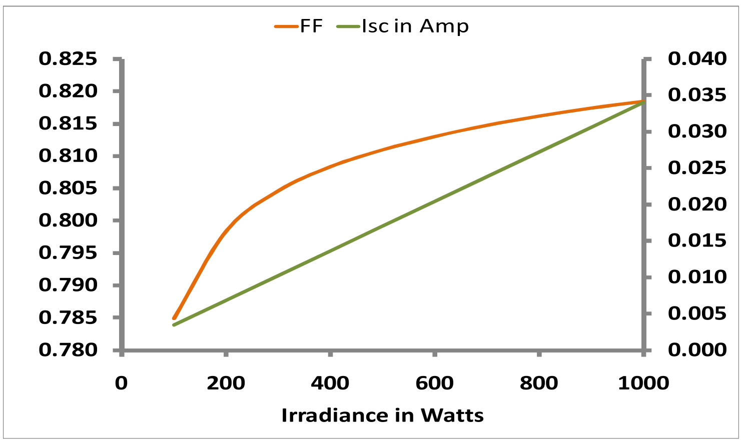

Figure 8. Effects of different irradiances on the fill factor and the short-circuit current.

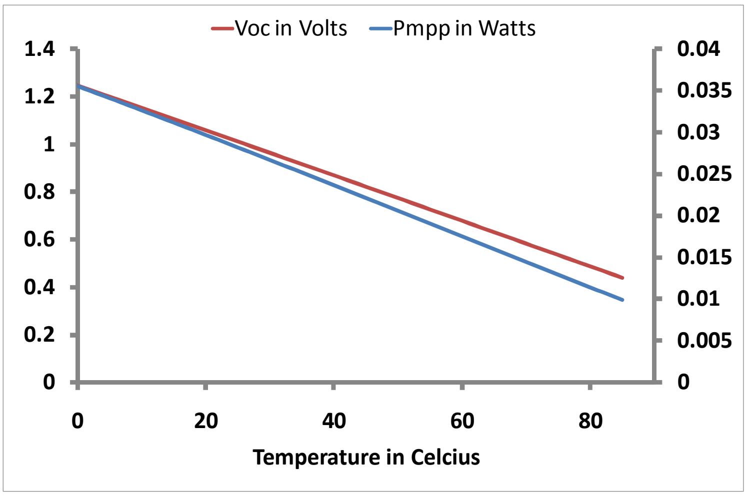

Figure 9. Effects of various temperatures on the power at the maximum point and the open-circuit voltage.

Effects of temperatures

Variations in module temperatures are influenced by factors such as wind speed, humidity and the mounting structures of the PV device. Temperature has significant impacts on the open-circuit voltage and maximum power. The increase in the cell temperature from 25℃ to 57℃ causes the voltage to drop from 1.02 Volt to 0.70 Volt as it is shown in Fig. 9. This is due to the changes in the band-gap energy of the individual sub-cells of a double junction solar cell. As shown in Fig.10, there is a slight increase in the short-circuit current with the increase in temperature condition. However, due to a large reduction in the open-circuit voltage with increasing temperature, the increase in the short-circuit current cannot increase the maximum power of the double-junction solar cell. The maximum power of the cell drops by a factor of 1.06% per degree Celsius.

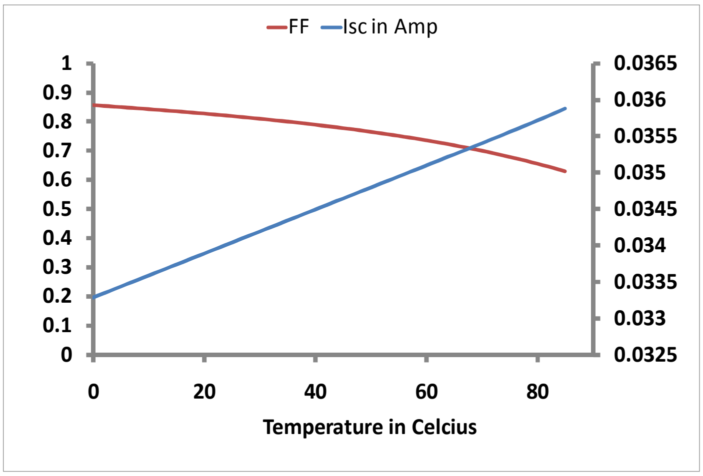

Figure.10. Effects of various temperatures on the fill factor and the short-circuit current of a double-junction solar cell.

Effects of solar spectrum

Solar spectrum changes with the sun positions during the day, dust particles, and the water content in the sky. In this study, the variations in the solar spectrum are expressed in terms of the air mass (AM) which is the thickness of the atmosphere that solar radiation must travel to reach the earth's surface. Variations in the solar spectrum produce the mismatched current between the top and bottom cells as shown in Fig. 11 and 12. The variations also affect the fill factor considerably. The Top cell becomes the current limiting junction at higher air mass (> AM 2.5) while the bottom cell becomes the current limiting junction of the cell at lower air mass. Changes in the short-circuit current are very significant with the changes in solar spectrum compared to other performance parameters.

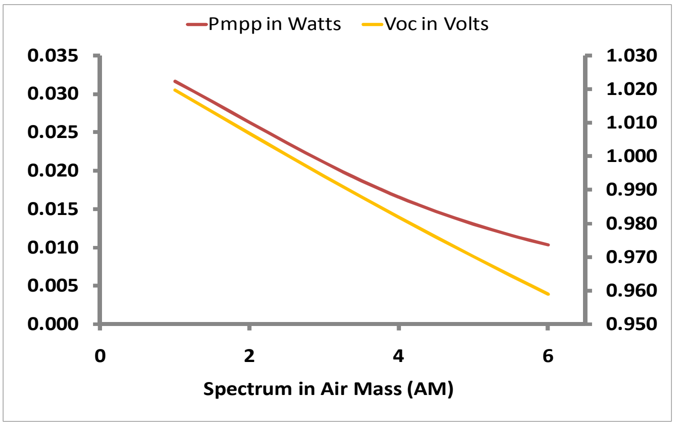

Figure 11. Effects of various spectra on the maximum power and the open-circuit voltage of a double-junction solar cell.

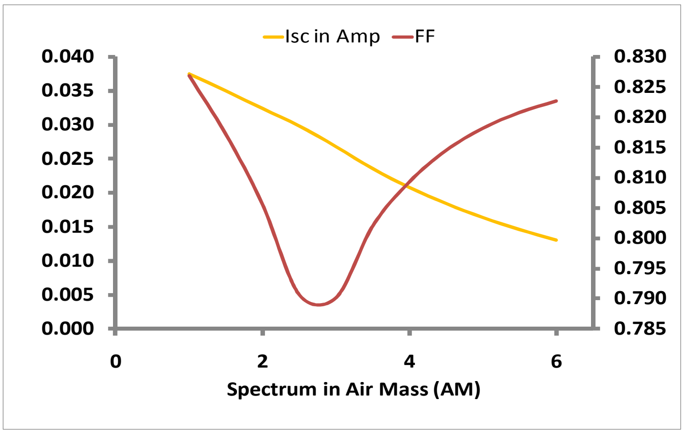

Figure 12. Effects of various spectra on the fill factor and the short-circuit current of a double-junction solar cell.

Effects of the angle of incidence

The angle of incidence (AoI) affects the incident irradiance received by a double-junction solar cell. The influences of angle of incidence on the device performance parameters are shown in table 2. The reduction in the maximum power is very significant at angle of incidence greater than 60°.

Table 2. Effects of variations in AoI on the performance parameters of a double-junction solar cell.

AoI	Voc [V]	Isc [Amp]	Pmax[Watt]
0	1.011	0.034	0.028
60	0.992	0.024	0.020
120	0.904	0.005	0.004

Conclusions

Different environmental factors have specific impacts on the performance parameters of a double-junction solar cell. The short-circuit current generated by the cell is considerably influenced by the irradiance level, the angle of incidence and the solar spectrum while the open-circuit voltage is significantly dependent on the cell temperature. The short circuit current of a double-junction solar cell becomes spectrally sensitive with the changes in the solar spectrum. This is due to the individual sub-cells respond differently to specific wavelengths of solar spectrum in converting photon energy into photocurrent. The reduction in the maximum power is very critical when the angle of incidence is greater than 60°.

References

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